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SUMMARY

An investigation has been conducted to determine which combination of method of counting and type of load programing best retains the essential fatigue-inducing characteristics of a random time history of stress. In an earlier investigation several time histories were numerically generated and counted by various methods. The data obtained in the earlier investigation were used in this investigation to conduct axial-load fatigue tests of 2024-T3 aluminum-alloy sheet specimens with notched edges. The fatigue life obtained from tests using the random peak history was used as a basis of comparison. The elimination of various sized fluctuations, due to the different counting methods, had little, if any, effect on fatigue life in tests using a random sequence of loads. Tests conducted by using ordered loading produced lives greater than the random fatigue life. The value of life in the ordered tests varied with the counting method, with statistical properties of the time history, and probably with the assumptions made in reducing the data to block form.

INTRODUCTION

The aircraft designer is well aware of the structural fatigue problems present in current aircraft. In order to offset the lack of adequate analytical design methods, common practice now is to evaluate new designs by conducting full-scale evaluation fatigue tests on prototype vehicles. If the random-load time histories encountered in service could be duplicated in a laboratory, the estimate of fatigue life from such a test would undoubtedly be considered reliable. However, existing fatigue-testing equipment is generally limited to applying simple cyclic loads. Thus, the designer must estimate service life from full-scale tests which use simplified test techniques.

Several counting methods have been devised to reduce a random-load history to numerical form. These counting methods produce several different sets of load statistics that can be used to program fatigue tests which simulate, with varying degrees of complexity, a random-load history. The purpose of this investigation is to determine whether fatigue tests, based on the load statistics obtained from the various counting methods, adequately retain the significant fatigue-inducing characteristics of a random-load history.

Four generated time histories were used in this investigation. Three of the time histories were taken from reference 1, and the fourth one, which had a bimodal power spectrum, was added to increase the scope of power spectra represented. The load statistics obtained from the various combinations of load history, counting method, and method of load-frequency-distribution simulation were used to conduct axial-load fatigue tests on 2024-T3 aluminum-alloy edge-notched sheet specimens with a theoretical elastic-stress concentration factor of four. Fatigue-life comparisons were made for each peak history.

The units used for the physical quantities defined in this paper are given both in the U.S. Customary Units and in the International System of Units (SI). Factors relating the two systems are given in reference 2.

TEST PROCEDURES

Test procedures include all the necessary preparation prior to conducting the fatigue tests. These preparations include the following: (1) preparation of the specimen; (2) a device for testing the specimen; (3) load statistics; and (4) load programs.

Specimens

The edge-notched specimen configuration (fig. 1) used in this investigation had a theoretical elastic-stress concentration factor of four. Material for specimens was part of a stock of commercial 0.090-inch (2.28 mm) thick 2024-T3 aluminum alloy retained at the Langley Research Center for fatigue tests. Selected tensile properties for this material are given in table I. (See ref. 3.)

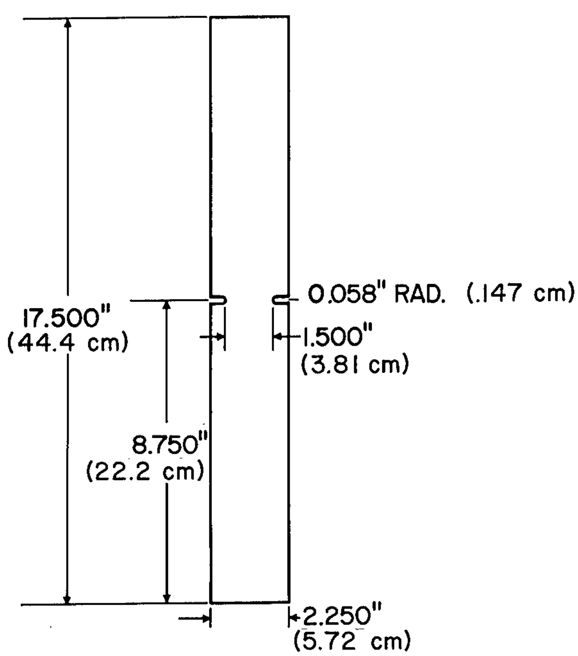


Figure 1.- Specimen configuration.

A specimen-numbering system, which identifies the specimen as to material, sheet number, and location within the sheet, has been established. For example, specimen A93N2-7 is 2024-T3 material A and was taken from N2 position of sheet 93. The 7 indicates the position within the material blank (A93N2) from which the specimen blank was taken. (See ref. 4.)

Specimen dimensions are shown in figure 1. The rolled surfaces were not modified and the longitudinal surfaces were machined and notched in both edges. The notches were formed by drilling

holes to form the notch radii. Residual machining stresses were minimized by first drilling with a small drill and then gradually increasing drill sizes (increment in diameter = 0.003 inch (0.076 mm)) until the proper radius was obtained. Specimens were drilled in stacks of 10. For consistency, drills were not used more than four times before being resharpened or replaced. The notches were completed by slotting with a 3/32-inch (2.4 mm) milling tool.

Burrs left in the machining process were removed by holding the specimen lightly against a rotating cone of 00 grade steel wool. All specimens were inspected and only those free of surface blemishes in and near the notch were tested.

Machines

Three servohydraulic machines were used in this investigation. A typical block diagram of one of the machines is shown in figure 2. The loading frame had a nominal capacity of ±20,000 pounds (±89.0 KN) in axial load. Cycle rates, which depended on the load range, reached 7 cps (7 Hz). The important features of this programed load-fatigue machine are: (1) 55 discrete load levels, each identified by its own code, can be preset to any value between zero and full scale; and (2) any type of load history defined by as many as 55 discrete load levels can be programed in any arbitrary sequence by using punched cards.

A detailed description of the machine is presented in reference 5. Basically, the machine is a closed-loop servo-controlled hydraulic machine which incorporates a rather sophisticated electrical network for load selecting and checking.

Loads are monitored by either a galvanometer recorder or a null-indicating a-c bridge. The recorder is used to scan for extraneous loads, whereas the

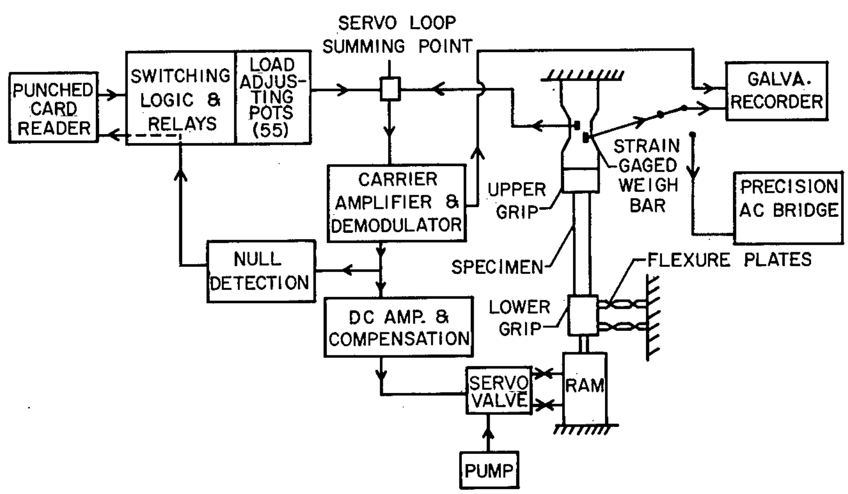


Figure 2.- Block diagram of programed axial-load fatigue machine.

a-c bridge is used to measure static loads and to check system damping. The whole system is calibrated periodically and the static-load indication is repeatable to 0.1 percent of full scale. Error in true load is less than 0.2 percent of full scale.

Load Statistics

In reference 1, a method is described for digitally generating a random time history independent of time. This time history was passed through numerical filters which had arbitrary shapes; thus, the resulting time histories had specified power spectral characteristics. Each of the power spectra had a common value for the area under the curve. (The standard deviation for each power spectrum was 1.)

Four time histories were used in this investigation: (1) white noise (time history A); (2) atmospheric turbulence (time history B); (3) single degree of freedom (time history C); and (4) a bimodal power spectrum (time history D). Time histories A, B, and C were random histories generated and analyzed in reference 1, and time history D was generated by the method described in this reference. The shape of the power spectrum for each of the time histories is shown in figure 3.

The time histories were converted to peak histories by omitting the numbers which did not define a peak (either positive or negative). This conversion, which was justified on the assumption that fatigue is more nearly cycle dependent than time dependent, compressed the time scale so that the power spectra of the modified histories would be expected to approach the shape of the spectrum shown for time history C. (See fig. 3.) The actual shapes, however, were not investigated in this study.

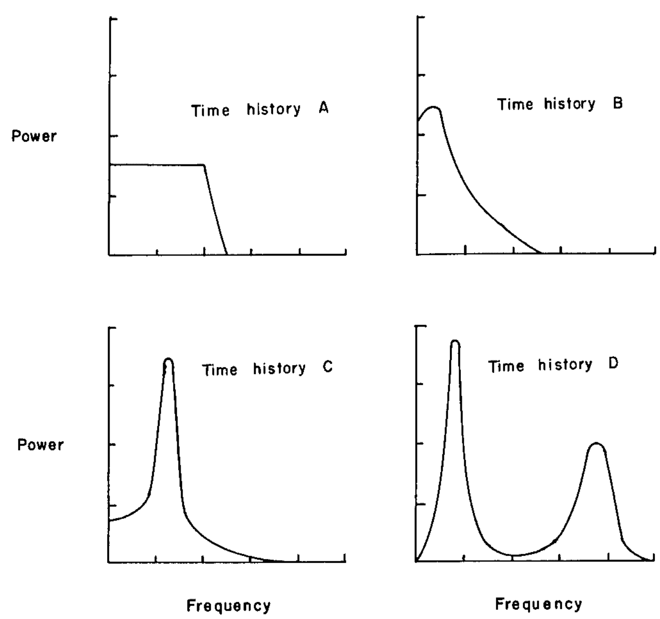


Figure 3.- Schematic representation of power spectra for four time histories. (Histories A, B, and C from ref. 1.)

The peak histories were reduced to sets of statistics which were based on several methods of counting the peak history. In addition, several methods of representing the results of the counts were used. In order to facilitate counting the peak history, the generated numbers were scaled so that all numbers fell between -5.0 and 5.0 on an arbitrary scale. The smallest fluctuation counted as a cycle had a range of 0.2 on the arbitrary scale. An amplitude is defined as one-half the algebraic difference of two adjacent peaks, and a mean is defined as one-half the algebraic

sum of two adjacent peaks. A positive amplitude has a positive slope when it crosses its associated mean. In reference 1 a statistical check was made to verify that the negative and positive distributions of events were the same; therefore, only the positive distributions are considered herein.

A detailed description of each counting method used is presented in reference 6. A title and brief description of the counting methods follows:

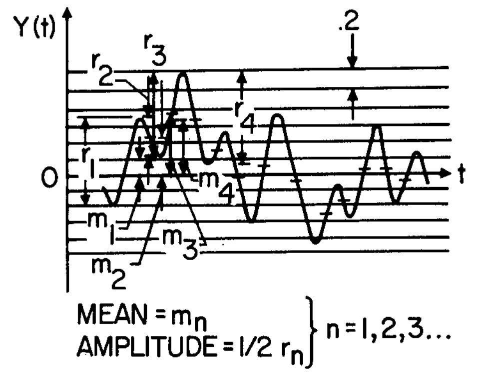
<u>Means and amplitudes</u>.- In the means and amplitudes counting method (fig. 4(a)), each peak-to-peak fluctuation is defined by a mean and an amplitude, and, considering the entire time history, it is apparent that each mean value would have a distribution of amplitudes. (See ref. 6.) Thus, the results of this counting method can be used to develop several different distributions for test purposes. (See discussion of loading programs.)

<u>Means and amplitudes eliminating small fluctuations</u>.- The means and amplitudes eliminating small fluctuations counting method (fig. 4(b)) is the same as the means and amplitudes counting method except that only the peak-to-peak fluctuations which exceed 0.4 on the arbitrary scale are counted.

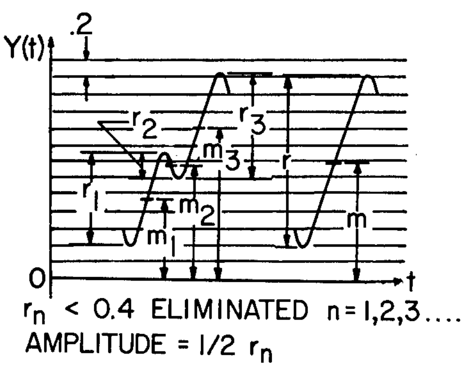
<u>Maximum peaks between zero crossings</u>.- In the maximum peaks between zero crossings counting method (fig. 4(c)), only the amplitude of the highest peak between successive crossings of the zero reference axis is counted.

<u>Level crossings</u>.- The level crossings counting method (fig. 4(d)) counts the number of times the time history crosses a given level with positive slope. The number of peaks occurring in the interval between two adjacent levels, which is not necessarily the true number of peaks in the interval, is obtained by subtracting the respective number of crossings at each of these levels. (See appendix B of reference 6.)

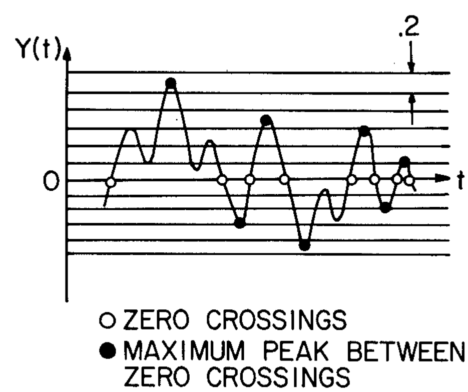
<u>Level crossings eliminating small fluctuations</u>.- The level crossings eliminating



(a) Means and amplitudes.

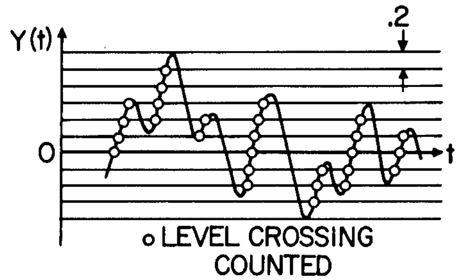


(b) Means and amplitudes eliminating small fluctuations.

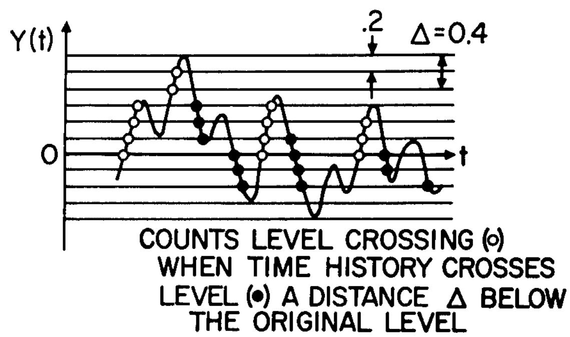


(c) Maximum peaks between zero crossings.

Figure 4.- Schematic representation of counting methods (from ref. 6).



(d) Level crossings.



(e) Level crossings eliminating small fluctuations.

Figure 4.- Concluded.

small fluctuations counting method (fig. 4(e)) is the same as the level crossings counting method except that the trace (with a negative slope) must cross a level a specified value lower than a given level before the higher level can be counted the next time the trace (with a positive slope) crosses. The specified value for this counting method was 0.4 on the arbitrary scale.

Load Programs

The data obtained by the various counting methods were used to program variable-amplitude fatigue tests. The following numerical relations were used to convert the distribution of peaks from the arbitrary scale (-5 to 5 in 0.2 intervals) to a load or stress scale: (1) on the arbitrary scale, 0 corresponded to a mean stress of 17.4 ksi (120.1 MN/m^2) on the specimen, and (2) on the arbitrary scale, 5 corresponded to the stress equal to the stress at design limit load 43.5 ksi (300.1 MN/m^2). One exception was made to assumption (2), in that for one series of tests, 4 on the arbitrary scale was made equal to the design limit load. For these tests peak values above 4 were applied at 4.

Load programs were developed in accordance with three types of load programing: random cycle, constant-mean-block, and varied-mean-block. These load programs are as follows:

Random tests.- Each of the random programs used 50 load levels, the sequence of load levels being retained from the analysis of the filtered time history. The 50 load levels corresponded to the upper limits of each of the 50 increments in the arbitrary scale. The distribution of positive peaks occurring in the positive range of the arbitrary scale for each filtered peak history and random test program is presented in table II(a). Complete descriptions of means and amplitudes for time histories A, B, and C are given in reference 1, whereas time history D is presented in table III.

Program 1: In program 1 the peaks were programed in accordance with the filtered time history. The life obtained using this load program was assumed to be the service life and was used as the basis of comparison for the lives obtained from tests using other load programs.

Program 2: In program 2 only the maximum peaks between zero crossings were applied.

Program 3: Program 3 used the peak values defined by the means and amplitudes eliminating small fluctuations counting method.

Constant-mean block tests.- The results of a given counting method were converted to the cumulative frequency distribution of stress. The distribution was divided into eight equal stress bands representing the positive peak distribution. For programs with design limit load equal to 5, each peak stress band was represented by a peak stress equal to the midstress of the band. For programs with design limit load equal to 4, the representative stresses were determined by a numerical integration process (similar to that employed in ref. 7). The number of cycles per block was arbitrarily taken to be approximately 4000 for programs with design limit load (DLL) equal to 5. For programs with DLL = 4, the number of cycles per block was selected so as to make the summation of cycle ratios approximately equal to 0.1 per block. Block sizes would then vary from 2000 to 6000.

For all block tests, each positive half cycle was followed by an equal negative half cycle. A positive half cycle is defined to be a stress excursion having a peak value algebraically larger than the mean to which it is referenced. Within each block, each load level occurred once and all cycles at that level were applied sequentially before proceeding to the next load level. Within each block, the sequence of load levels was made random in accordance with a schedule taken from a table of random numbers. A different randomization was used for each of the first 20 blocks, after which the random blocks were repeated starting with the first block.

The following load programs were developed for constant-mean block tests; the distributions used for each combination of program and peak history are given in table II(b).

Program 4: Program 4 used the cumulative frequency distribution obtained from the maximum peaks between zero crossings counting method; and had the same average distribution of positive peaks as program 2.

Program 5: The cumulative frequency distribution of positive peaks occurring in the positive range of the arbitrary scale was used in program 5. This distribution was derived from the statistics obtained in the means and amplitudes counting method. For this program, each peak was preceded and succeeded by a zero crossing.

Program 6: Program 6 used only the amplitudes from the means and amplitudes counting method. All amplitudes were applied as though they had occurred about the zero reference line of the arbitrary scale.

Program 7: Program 7 used the cumulative frequency distribution obtained from the level crossings counting method.

Program 8: Program 8 used the cumulative frequency distribution obtained from the level crossings eliminating small fluctuations counting method.

Varied-mean block tests.- The same general guide lines used for the constant-mean block tests were used for load programs in which the mean was

varied. The same eight levels were used to represent the range of stress, but instead of grouping all the means at the zero reference, three positive and three negative means were added. Therefore, seven distributions of positive peaks relative to the seven means were obtained, and each distribution was represented by 3, 5, 7, or 8 stress amplitudes. In order to facilitate programing, the means were selected at stress-band boundaries. Therefore, by using the half-band value as the representative stress, the same load levels used in the constant-mean block tests were used in these tests. With this approach there are 38 possible combinations of means and amplitudes available. As in the constant-mean block tests, each combination of mean and amplitude was programed once each block and all cycles for that combination were applied sequentially. The first 20 blocks each had a different random sequence of load levels and these random blocks were repeated starting with the first block.

The following load programs were developed for varied-mean block tests; the distributions used for each combination of peak history and counting method are given in table II(c).

Program 9: Program 9 used cumulative frequency distributions obtained from the means and amplitudes counting method.

Program 10: Program 10 used cumulative frequency distributions obtained from the means and amplitudes eliminating small fluctuations counting method.

RESULTS

The results of variable-amplitude fatigue tests of 2024-T3 aluminum-alloy specimens are presented in table IV and figure 5. In figure 5, the symbols represent the geometric mean of six tests conducted with the same load program. The scatter in the test data for a given load program seldom exceeded $1\frac{1}{3}$ to 1, a trend which is in agreement with other variable-amplitude fatigue tests conducted at the NASA Langley Research Center. (See refs. 5, 7, 8, and 9.)

For a basis of comparison the fatigue life obtained in program 1 was assumed to be service life. It would not be realistic to compare either the peak histories or the various counting methods for a given peak history by comparing the number of cycles to failure, because each peak history and counting method eliminated various numbers of the cycles from the original time history. Therefore, the basis of comparison selected was the amount (or time) of the filtered time history traversed before failure, for each combination of peak history and counting method. The basis for this conversion of cycles to time was arbitrarily selected as the number of peaks occurring in 5000 numbers in the filtered time history. It should be noted that in the original time history each generated random number was assumed to be a point equally spaced timewise from adjacent points, and that positive and negative peak distributions were symmetrical. (See ref. 1.) The equivalent life for each test condition, in increments of the time for the filtered time history, is equal to the total number of cycles to failure divided by the average total number of peaks per

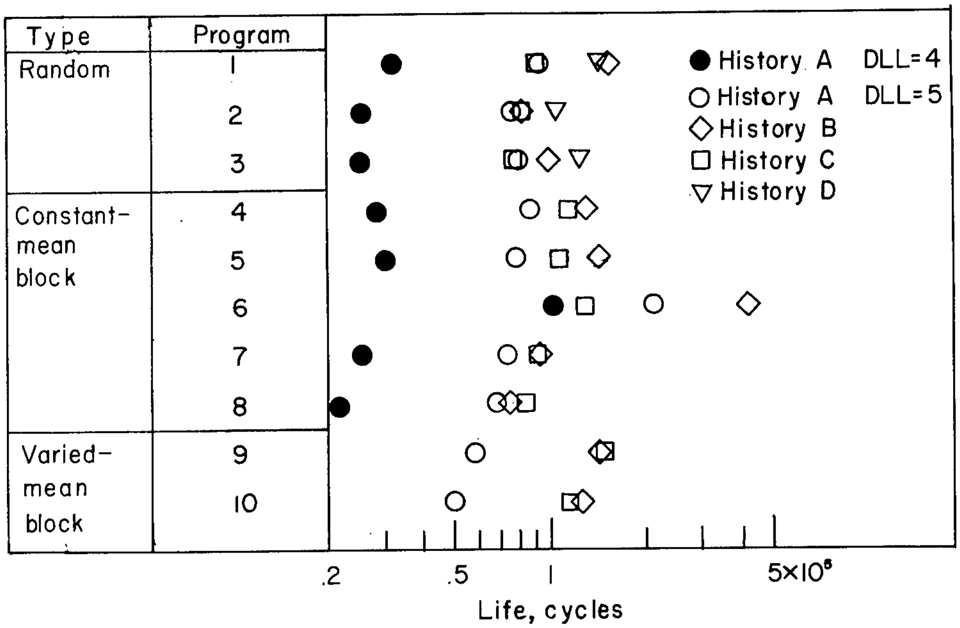


Figure 5.- Results of variable-amplitude fatigue tests. Symbols represent geometric mean life of six tests.

5000 numbers in the filtered time history. The ability of any counting method (for a given peak history) to retain the fatigue-inducing characteristics of the peak history is evaluated by comparing the number of increments of the time history survived with the service life.

Table V presents a summary of the data obtained in this investigation. The geometric mean lives, the average number of cycles per 5000 numbers, the equivalent length of time history survived, and the normalized life for each combination of peak history and counting method used are presented in this table. The normalized lives for each peak history are shown in figure 6. Each symbol represents the geometric mean of six tests conducted with the same load program.

DISCUSSION OF RESULTS

The schematic representation of the results of the variable-amplitude fatigue tests shown in figure 5 illustrates the very small variation in mean life obtained in these tests (except shaded points) regardless of peak history or counting method used. As can be seen, more than 90 percent of the mean lives fall within the range 75,000 to 150,000 cycles.

The shaded symbols in figures 5 and 6 are data points obtained in tests with a design limit load of 4.0 on the arbitrary scale. It was found that this method produced load distributions which resulted in very short fatigue lives, and thus tended to minimize any systematic influences which might have been present. It should be noted, however, that the trends obtained in these tests

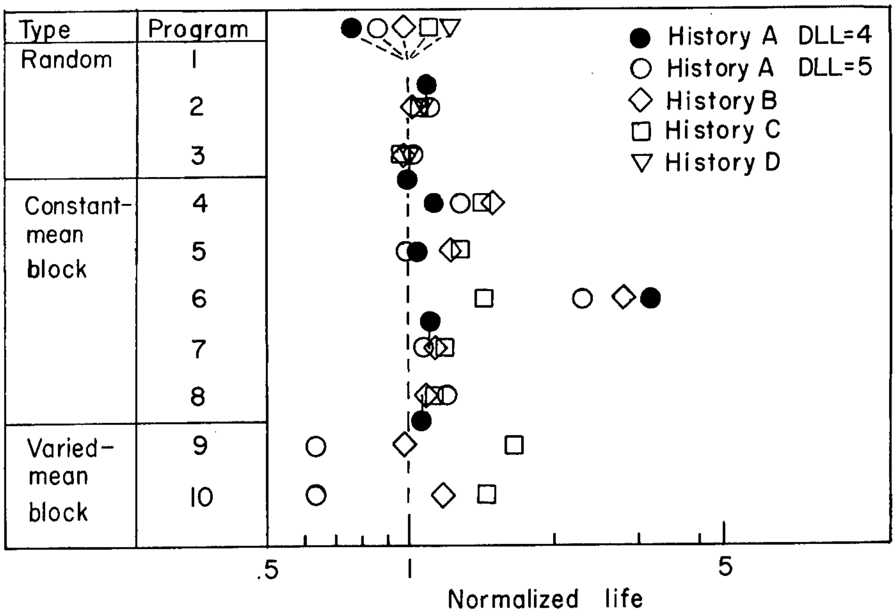


Figure 6.- Results of variable-amplitude fatigue tests. Symbols represent geometric mean of normalized life of six tests.

are the same with respect to the load programs as those obtained in the tests with a design limit load of 5.0 on the arbitrary scale.

A comparison of the peak values obtained from each peak history for the same counting method reveals cumulative frequency distributions which are essentially the same. Figure 7 shows the distributions: (1) the maximum peaks obtained for the means and amplitudes counting method; (2) the maximum peaks obtained for the maximum peaks between zero crossings counting method; and (3) the maximum peaks obtained for the level crossings counting method. Although statistical tests may indicate that these distributions are significantly different, their use resulted in approximately the same fatigue life.

Random Tests

The values of normalized life for each of the data points for random test programs 2 and 3 are found to be very closely grouped around a value of 1.0. (See table V and fig. 6.) The average value of normalized life for the maximum peaks between zero crossings counting method (program 2) was slightly higher than 1.0. This result seems reasonable because large amplitude cycles can be eliminated by this counting method, and fatigue life is thus increased. The average value of normalized life for the means and amplitudes eliminating small fluctuations counting method (program 3) was slightly less than 1. If these differences are real, they may be due to omitted cycles in program 2 and increased cycle amplitudes in program 3 due to the elimination of small fluctuations. Fatigue tests conducted with programs 2 or 3 would appear to provide an adequate estimate of fatigue life.

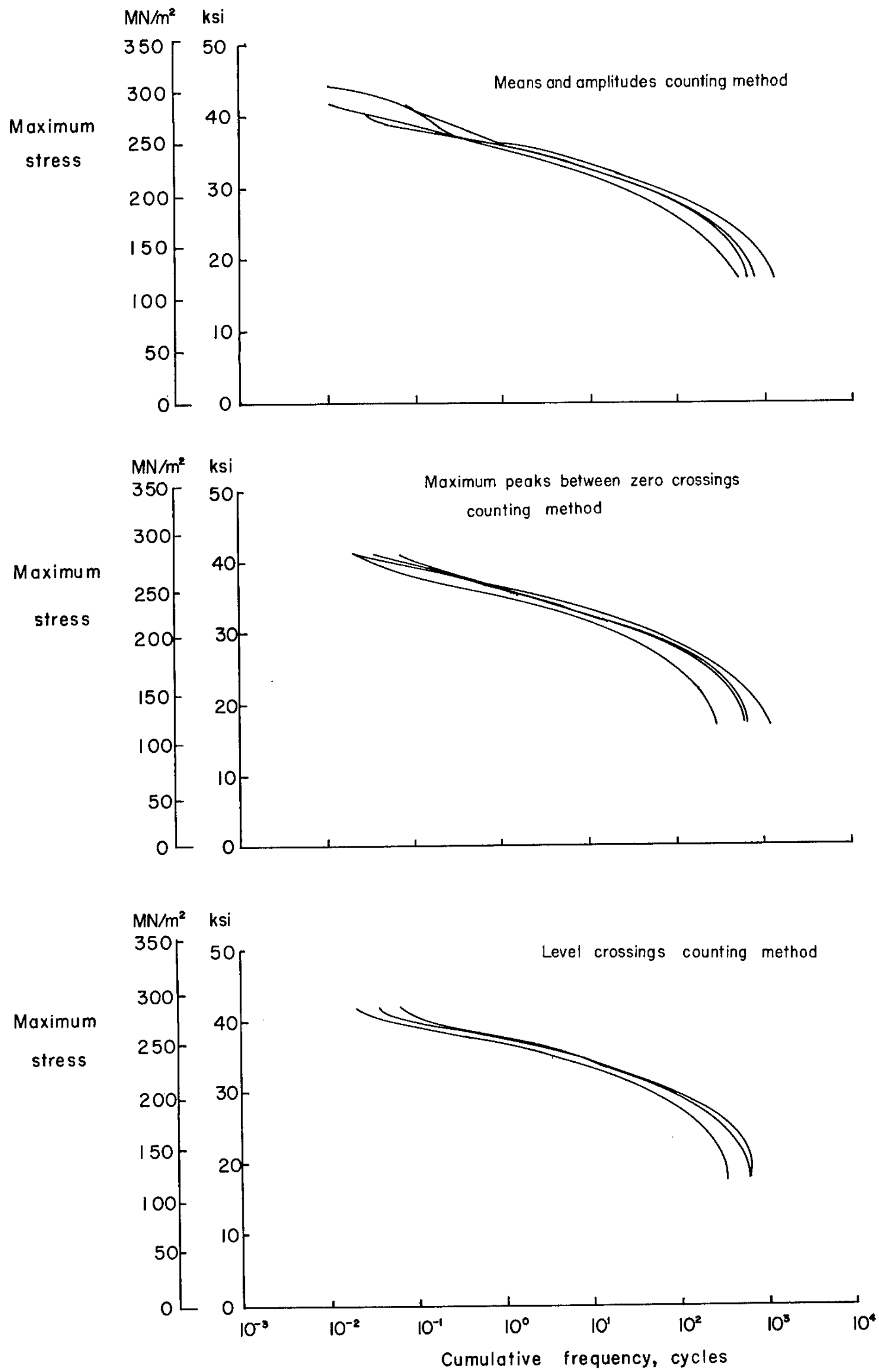


Figure 7.- Peak stress distributions of time histories tested for three counting methods.

Constant-Mean Block Tests

In the following discussion of the results of constant-mean block tests, some of the characteristics of block tests, in general, should be recalled. Among the characteristics which may influence the lives obtained in this investigation are: (1) block tests, in general, have longer lives than random tests (ref. 5); (2) the number of cycles per block (block size) may in some cases influence fatigue life (refs. 7 and 8); and (3) the assumptions made in developing the various counting methods automatically eliminate all mean stresses other than the reference mean stress, and thus reduce the strong influence of mean stress on fatigue life.

The effect on fatigue life of items (1) and (2) is discussed in some detail in the cited references and will not be reiterated here. The importance of item (3) will be noted in particular in subsequent discussions of the data obtained in this investigation and therefore requires additional comment. In reference 1, an analysis of the probability of equaling or exceeding a given value of a mean is presented. Figure 8 (data from ref. 1) shows the probability distributions for the peak histories used in this investigation. In figure 8, the slope of the curve is a measure of the dispersion of individual means about the reference mean. Therefore, when a given counting method compressed all means to the reference mean, the effect on fatigue life will be greatest for the peak history with the greatest dispersion of mean stresses.

The average value of the normalized life for constant-mean block tests using load programs 4, 5, 7, and 8 are greater than 1.0. (See table V and fig. 6.) Each group of data for a given counting method would be expected to be ordered according to increasing mean stress dispersion of the peak histories. This trend is present to some degree but is not completely established.

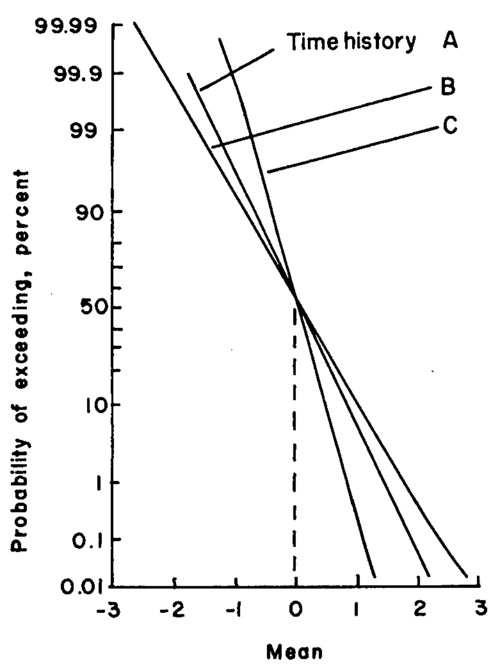


Figure 8.- Representation of mean stress dispersion for three time histories.

The results of tests using load program 6 show a very decided increase in life over the reference life (program 1). The primary reason for this increase appears to be the suppression of mean stress dispersion, which reduced the peak stress values for each peak history and thus produced a net increase in fatigue life. These results agree qualitatively with those reported in reference 10.

From the foregoing discussion it appears reasonable to expect that the use of constant-mean block tests generally will produce normalized lives greater than 1.0. The value of normalized life will vary with the counting method, with statistical properties of the time history, and probably with the assumptions made in reducing the data to block form.

Varied-Mean Block Tests

The results of the varied-mean block tests (table V and fig. 6) show that a wide range of values of normalized life are obtained. The data do not indicate a consistent trend. However, it should be noted that the effects due to techniques associated with block tests using multiple means have not been fully investigated. The variations in the results cannot be explained. It does not appear that this type of load programing provides a consistent estimate of fatigue life.

CONCLUDING REMARKS

Fatigue tests were conducted by using the peak values from four random peak histories, each having a different power spectrum. The peak values were assigned arbitrary stress values and were applied to edge-notched sheet specimens of 2024-T3 aluminum alloy. Companion fatigue tests were conducted by using the results of several counting methods and employing three testing techniques: (1) retention of original sequence, (2) application in a block sequence with constant mean stress, and (3) application in blocks with varied mean stress. The results were compared to determine the combination of counting method and testing technique which retained the essential fatigue-inducing characteristics of a generated random time history.

The tests using random peak histories resulted in essentially equal fatigue lives for all four power spectra. Although the power spectra of the four time histories were quite different, the peak stress distributions were very similar.

The tests which used random sequences modified according to several counting procedures resulted in fatigue lives equivalent to those obtained before counting. Apparently, lives were not affected by the fact that the counting procedures systematically eliminated certain fluctuations in the time history.

The constant-mean block tests resulted in fatigue lives generally greater than those for the peak histories. Suppression of mean stress dispersion, which is inherent in block tests, is probably the most important factor responsible for this behavior. In addition, earlier tests have shown that block tests produced longer lives than random tests if the same stress-frequency distribution is used. The degree of variation is dependent upon both counting method and statistical properties of the time history.

Varied-mean block tests produced widely dispersed lives which were not amenable to reasonable interpretation.

End

The results of this investigation indicate that additional experimental and analytical work is necessary to determine the basic fatigue-inducing characteristics of a given time history.

Langley Research Center,
National Aeronautics and Space Administration,
Langley Station, Hampton, Va., October 26, 1964.

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TABLE I.- TENSILE PROPERTIES OF MATERIAL TESTED

[Data from reference 5; 2024-T3 (147 tests)]

Property	Average	Minimum	Maximum
Yield stress (0.2% offset),			
ksi	52.05	46.88	59.28
MN/m^2	358.6	323.0	408.4
Ultimate tensile strength,			
ksi	72.14	70.27	73.44
MN/m^2	497.0	484.2	506.0
Total elongation (2 in. (5.08 cm) gage length), percent	21.6	15.0	25.0

TABLE II.- LOAD PROGRAMS USED FOR VARIABLE-AMPLITUDE FATIGUE TESTS OF 2024-T3 ALUMINUM-ALLOY SPECIMENS

[S_{mean} = 17.4 ksi (120.06 MN/m^2)]

(a) Random tests

Load level	Stress amplitude (a)		Relative frequency of occurrence of positive peaks per 5000 filtered numbers											
			Peak history A			Peak history B			Peak history C			Peak history D		
	ksi	MN/m^2	Program 1	Program 2	Program 3	Program 1	Program 2	Program 3	Program 1	Program 2	Program 3	Program 1	Program 2	Program 3
1	0.5	3.6	54	49	0	41	34	0	34	27	0	122	115	0
2	1.6	10.8	65	52	11	46	31	5	48	36	18	145	124	27
3	2.6	18.0	74	58	33	50	29	15	61	50	46	159	125	71
4	3.6	25.2	81	63	50	51	29	24	71	64	65	168	126	106
5	4.7	32.4	81	63	60	48	28	27	75	72	73	165	123	126
6	5.7	39.6	76	62	60	44	27	30	74	73	73	148	111	126
7	6.8	46.9	70	60	59	40	26	30	66	66	66	129	100	117
8	7.8	54.0	60	54	52	33	24	57	57	57	57	104	85	98
9	8.9	61.2	49	45	43	25	20	21	48	48	48	80	67	77
10	9.9	68.5	35	34	32	21	17	18	36	36	36	59	51	58
11	11.0	75.6	26	25	24	14	13	13	27	27	26	41	37	41
12	12.0	82.9	19	18	17	11	10	10	18	18	18	27	25	27
13	13.0	90.0	12	11	10	7	7	7	13	13	13	17	16	17
14	14.1	97.2	8	8	7	5	5	4	8	8	8	10	9	10
15	15.1	104.5	5.1	5.1	4.6	2.5	2.5	2.4	4.5	4.5	4.5	5.7	5.5	5.7
16	16.2	111.6	2.6	2.6	2.3	1.4	1.4	1.3	3.1	3.1	3.1	3.5	3.3	3.5
17	17.2	118.9	1.3	1.75	1.2	.86	.86	.73	1.5	1.5	1.5	1.8	1.8	1.8
18	18.3	126.0	.88	.86	.75	.44	.42	.44	.84	.84	.84	.92	.91	.92
19	19.3	133.2	.27	.26	.25	.23	.23	.22	.36	.36	.34	.28	.28	.28
20	20.4	140.5	.08	.08	.08	.06	.06	.05	.13	.13	.13	.23	.23	.23
21	21.4	147.7	.06	.06	.06	.03	.03	.03	.11	.11	.11	.05	.05	.05
22	22.4	154.9	.03	.03	.03	.02	.02	.02	.02	.02	.02	.05	.05	.05
23	23.5	162.1	.02	.02	.02	.02	.02	.02	.02	.02	.02	.02	.02	.02
24	24.5	169.3	.05	.05	.05	0	0	0	0	0	0	0	0	0
25	25.6	176.5	0	0	0	0	0	0	0	0	0	.02	.02	.02

[a]For tests in which design limit load was equal to 4.0 on the arbitrary scale increase each amplitude 20% not to exceed 25.6 ksi (176.5 MN/m^2).

TABLE II.- LOAD PROGRAMS USED FOR VARIABLE-AMPLITUDE FATIGUE TESTS

OF 2024-T3 ALUMINUM-ALLOY SPECIMENS - Continued

(b) Constant-mean block tests

Load level	Stress amplitude, ksi	Stress amplitude, MN/m^2	Relative frequency of occurrence of positive peaks per 5000 filtered numbers: Program 4	Program 5	Program 6	Program 7	Program 8
Peak history A (DLL = 4.0)							
1	2.40	16.6	517	595	1705	310	93
2	5.40	37.3	579	730	2148	647	562
3	8.40	58.0	522	612	1575	521	544
4	11.50	79.4	367	359	678	367	367
5	14.70	101.4	182	175	165	181	181
6	17.80	122.8	66.5	64.5	26.5	66.5	66.5
7	20.95	144.6	15.5	15.5	1.8	15.5	15.5
8	24.00	165.6	2.25	2.25	.1	2.25	2.25
			2251.25	2553.25	6299.4	2110.25	1831.25
Peak history A (DLL = 5.0)							
1	1.63	11.3	1081	934	1365	524	763
2	4.89	33.7	1287	1475	1651	1490	1505
3	8.16	56.3	1009	1027	803	1280	1118
4	11.42	78.8	483	439	178	547	478
5	14.68	101.3	134	120	18.5	150	131
6	17.94	123.8	19.67	18	.5	22.5	19.6
7	21.21	146.4	1.50	1.2	0	1.5	1.3
8	24.47	168.8	.33	.3	0	.4	.3
			4015.5	4014.5	4016.0	4015.4	4016.2
Peak history B							
1	1.63	11.3	1372	1515	2000	800	400
2	4.89	33.7	1224	1339	1340	1400	1400
3	8.16	56.3	823	715	520	1090	1320
4	11.42	78.8	456	330	127	530	650
5	14.68	101.3	112	83	12.5	155	200
6	17.94	123.8	20	14	.4	23	27.5
7	21.21	146.4	2.5	1.5	.1	2	2.2
8	24.47	168.8	0	0	0	0	.2
			4009.5	3997.5	4000.0	4000.0	3999.9
Peak history C							
1	1.63	11.3	1022	1171	1000	800	1000
2	4.89	33.7	1477	1425	1400	1500	1000
3	8.16	56.3	956	888	1100	1070	1260
4	11.42	78.8	401	386	400	465	550
5	14.68	101.3	135	108	88	139	163
6	17.94	123.8	11	17	11.3	24	24.3
7	21.21	146.4	2	1.5	.6	2	2.5
8	24.47	168.8	0	0	.1	0	.1
			4004.0	3996.5	4000.0	4000.0	3999.9

TABLE II.- LOAD PROGRAMS USED FOR VARIABLE-AMPLITUDE FATIGUE TESTS OF

2024-T3 ALUMINUM-ALLOY SPECIMENS - Concluded

(c) Varied-mean block tests

Mean stress		Load level	Stress amplitude		Relative frequency of occurrence at positive peaks per 5000 filtered numbers					
					Peak history A		Peak history B		Peak history C	
ksi	MN/m^2		ksi	MN/m^2	Program 9	Program 10	Program 9	Program 10	Program 9	Program 10
1.09	7.52	1	1.63	11.3	2	0.2	29	10	0	0
		2	4.89	33.7	1.4	1	8.5	7.5	0	0
		3	8.16	56.3	1.2	.8	2.2	1.5	0	0
7.61	52.51	1	1.63	11.3	40	6	220	120	8	1
		2	4.89	33.7	43	26	130	115	5.6	3
		3	8.16	56.3	49	40	41	59	3.4	4.2
		4	11.42	78.8	14	15	7.8	14.8	1.8	1.7
		5	14.68	101.3	4	4	1.1	1.1	.2	.1
14.14	97.57	1	1.63	11.3	274	114	450	300	190	115
		2	4.89	33.7	325	308	300	400	260	260
		3	8.16	56.3	236	250	117	182	182	220
		4	11.42	78.8	114	119	29.2	51	73	82
		5	14.68	101.3	27	30	3.7	6.3	16.3	16.2
		6	17.94	123.8	4	5	.1	.2	1.4	1.3
		7	21.21	146.4	.25	.25	0	0	.3	.3
17.4	120.06	1	1.63	11.3	188	114	600	400	700	500
		2	4.89	33.7	256	200	44	640	890	1100
		3	8.16	56.3	214	225	168	311	610	660
		4	11.42	78.8	85	90	37.5	90	235	273
		5	14.68	101.3	22	23	4.2	9	57	59
		6	17.94	123.8	4	4	.3	.2	7.7	7.6
		7	21.21	146.4	.3	.5	0	0	.3	.3
		8	24.47	168.8	0	0	0	0	0	.1
20.66	142.55	1	1.63	11.3	370	114	460	300	200	100
		2	4.89	33.7	325	296	310	410	270	250
		3	8.16	56.3	251	262	118	203	185	250
		4	11.42	78.8	104	118	29	60	77	80
		5	14.68	101.3	27.9	31	3	6.5	16	18
		6	17.94	123.8	4.5	4.5	.1	0	1.7	1.7
		7	21.21	146.4	.3	.3	0	0	.2	.2
27.19	187.61	1	1.63	11.3	43	15	285	110	7	1
		2	4.89	33.7	46	31	72	116	5	32
		3	8.16	56.3	37	32	34	57	4.5	4.6
		4	11.42	78.8	16	16	8.1	15.5	1.9	2.4
		5	14.68	101.3	3	3	.8	1.5	.5	.7
33.71	232.60	1	1.63	11.3	1.2	.5	35	9	0	0
		2	4.89	33.7	1.4	.5	9	8	0	0
		3	8.16	56.3	.4	.5	1.2	1	0	0

TABLE III.- FREQUENCY OF OCCURRENCE OF MEANS AND AMPLITUDES FOR TIME HISTORY D (BIMODAL)

Amplitude	Frequency of occurrence of mean -																										
	0.0	-0.2	+0.2	-0.4	+0.4	-0.6	+0.6	-0.8	+0.8	-1.0	+1.0	-1.2	+1.2	-1.4	+1.4	-1.6	+1.6	-1.8	+1.8	-2.0	+2.0	-2.2	+2.2	-2.4	+2.4	-2.6	+2.6	Total
-0.1	569	527	523	463	457	349	369	248	261	157	160	94	92	48	47	24	23	7	8	6	6	1	2					4441
+.1	598	544	540	467	468	360	361	256	257	160	164	94	91	59	54	26	25	10	10	7	5	2	4					4562
-.3	886	851	836	717	730	528	545	402	384	230	254	144	153	66	74	35	36	17	21	6	5	4	3	1	2	1		6931
+.3	871	844	811	681	713	542	537	380	393	260	225	132	153	65	76	33	37	19	10	4	3	4	2		1			6796
-.5	1067	993	1035	934	941	699	684	488	475	303	305	193	177	100	95	43	40	20	28	7	5	1	0	3	1			8637
+.5	1071	1020	1002	906	891	708	711	502	494	297	322	179	181	108	107	47	37	20	20	6	8	2	2	1				8642
-.7	1170	1080	1170	933	1042	732	894	550	728	331	490	189	343	130	210	55	108	20	56	14	24	3	7	2	3			10284
+.7	1116	1066	1040	937	944	721	689	522	523	320	313	181	195	122	105	55	53	17	23	11	8	1	5	3	1	1		8973
-.9	974	911	931	813	819	641	647	452	435	288	307	175	182	103	100	54	44	22	25	12	9	2	5	1	2			7954
+.9	1029	971	906	832	845	651	630	470	478	298	278	172	187	94	109	51	51	20	21	10	13	2	5	0	0			8123
-1.1	787	731	718	618	643	487	505	362	348	231	219	151	140	75	87	40	41	16	18	10	5	1	5	2	0			6240
+1.1	762	742	709	650	625	455	497	346	364	244	234	151	147	79	85	43	37	13	19	7	7	3	3	1	0		1	6224
-1.3	530	515	493	418	400	318	327	260	242	139	178	96	88	58	56	32	34	13	19	3	6	3	1	0	1			4230
+1.3	548	470	495	434	413	334	328	227	240	159	157	98	102	55	55	29	19	13	15	4	6	1	1	1	2			4206
-1.5	288	305	328	246	261	186	182	139	136	100	105	58	55	40	30	20	19	11	8	3	2		3	0	1			2526
+1.5	314	290	299	245	266	193	206	142	147	91	93	71	59	34	39	16	18	8	7	5	7	1	0	1				2552
-1.7	175	148	166	138	148	107	125	76	71	42	45	31	36	26	19	8	8	7	7	2	1	3	1	1				1391
+1.7	165	152	164	137	126	102	113	70	60	50	47	31	30	30	19	12	11	4	4	3	2	1						1333
-1.9	79	71	73	74	73	51	44	34	37	21	24	13	16	9	12	7	5	1	1	1	1							647
+1.9	85	91	79	57	75	43	54	38	34	28	23	14	18	11	10	3	6	2	4	1	2							678
-2.1	51	41	32	29	24	26	32	12	19	12	12	2	4	3	4	2	2	1	1	0	0							309
+2.1	45	34	31	40	28	20	22	16	12	8	11	4	7	5	3	2	1	0	1	1	1							292
-2.3	21	13	17	17	10	9	9	7	6	4	6	5	5	2	0	0	1	0	0									132
+2.3	26	19	19	12	15	15	7	5	5	3	5	2	4	2	0	1	0	0	1									141
-2.5	7	6	8	4	10	5	2	3	3	2	2	3	1	0	0													56
+2.5	10	7	10	10	10	4	3	2	3	1	0	1	0	0	1													62
-2.7	4	3	2	1	2	0	0	0	1																			13
+2.7	1	6	6	2	4	2	2	3	0	2																		28
-2.9	0	2	0	0	0	1																						3
+2.9	2	1	0	0	1	1																						5
-3.1	0	0	1																									1
+3.1	2	1																										3
-3.3	0																											0
+3.3	0																											0
-3.5	1																											1
Total	12254	12455	12444	10815	10984	8290	8525	6012	6166	3781	3979	2284	2466	1324	1398	638	656	261	327	123	126	35	49	17	14	2	1	106426

TABLE IV.- RESULTS OF VARIABLE-AMPLITUDE FATIGUE TESTS OF 2024-T3 ALUMINUM-ALLOY SPECIMENS

(a) Peak history A (design limit-load = 4.0 on scale)

Program	Specimen	Cycles	Program	Specimen	Cycles
1	A33N2-2	36,015	2	A85N2-2	31,045
	A86N2-3	36,015		A37N2-7	26,670
	A85N2-3	33,215		A30N2-8	25,025
	A79N2-5	32,305		A30N2-6	24,710
	A87N2-10	28,245		A85N2-5	23,940
	A34N2-2	28,070		A37N2-8	23,695
	Geometric mean	32,140		Geometric mean	25,760
3	A79N2-10	30,555	4	A78N2-1	31,272
	A83N2-3	29,225		A87N2-6	29,089
	A84N2-6	27,125		A86N2-5	29,055
	A86N2-4	23,975		A79N2-8	27,049
	A37N2-9	22,085		A28N2-2	27,109
	A30N2-2	21,070		A83N2-9	23,668
	Geometric mean	25,410		Geometric mean	28,800
5	A87N2-1	35,536	6	A85N2-7	119,828
	A79N2-9	33,019		A82N2-7	119,793
	A79N2-6	32,984		A80N2-7	101,631
	A86N2-9	29,310		A30N2-4	101,631
	A30N2-9	26,757		A34N2-10	88,366
	A30N2-7	26,197		A86N2-6	88,191
	Geometric mean	30,400		Geometric mean	102,500
7	A37N2-10	30,593	8	A84N2-10	24,220
	A30N2-3	29,323		A78N2-2	23,585
	A82N2-6	24,298		A28N2-8	23,375
	A34N2-5	24,158		A84N2-2	15,925
	A82N2-4	24,123		A82N2-8	21,124
	A84N2-5	24,123		A28N2-9	21,124
	Geometric mean	26,000		Geometric mean	21,350

TABLE IV.- RESULTS OF VARIABLE-AMPLITUDE FATIGUE TESTS OF

2024-T3 ALUMINUM-ALLOY SPECIMENS - Continued

(b) Peak history A (design limit-load = 5.0 on scale)

Program	Specimen	Cycles	Program	Specimen	Cycles
1	A82N2-1	98,053	2	A80N2-4	92,085
	A82N2-2	94,710		A78N2-9	79,170
	A84N2-4	94,710		A78N2-10	73,990
	A81N2-10	91,560		A84N2-7	72,905
	A79N2-4	89,250		A80N2-9	70,245
	A87N2-2	87,640		A84N2-3	66,710
	Geometric mean	92,580		Geometric mean	75,470
3	A82N2-3	91,945	4	A87N2-5	99,767
	A81N2-7	89,600		A81N2-8	91,351
	A78N2-6	80,325		A82N2-10	88,376
	A87N2-3	74,585		A110N2-10	83,180
	A83N2-10	73,920		A87N2-8	81,605
	A84N2-8	68,775		A85N2-8	76,399
	Geometric mean	79,430		Geometric mean	86,460
5	A83N2-7	88,353	6	A106N2-4	248,654
	A79N2-1	85,669		A106N2-7	237,959
	A106N2-3	77,641		A98N2-8	224,931
	A85N2-4	74,326		A107N2-10	212,822
	A105N2-9	74,326		A98N2-10	177,439
	A87N2-4	72,646		A107N2-7	177,369
	Geometric mean	78,610		Geometric mean	211,300
7	A98N2-7	88,391	8	A106N2-2	84,892
	A106N2-10	82,004		A79N2-3	76,493
	A105N2-7	76,379		A107N2-9	66,493
	A106N2-9	74,462		A105N2-6	64,953
	A107N2-8	63,148		A105N2-8	62,407
	A98N2-9	60,243		A85N2-6	62,372
	Geometric mean	73,430		Geometric mean	69,100
9	A109N2-2	71,330	10	A116N2-4	55,265
	A110N2-7	60,235		A100N2-5	49,490
	A108N2-1	58,415		A108N2-3	49,490
	A108N2-2	56,105		A116N2-3	49,175
	A110N2-9	52,710		A116N2-5	49,175
	A93N2-6	51,415		A101N2-4	44,555
	Geometric mean	58,020		Geometric mean	49,430

TABLE IV.- RESULTS OF VARIABLE-AMPLITUDE FATIGUE TESTS OF 2024-T3 ALUMINUM-ALLOY SPECIMENS - Continued

(c) Peak history B

Program	Specimen	Cycles
1	A91N2-5	173,215
	A113N2-10	161,175
	A111N2-10	151,900
	A17N2-9	143,115
	A104N2-7	141,890
	A102N2-7	140,245
	Geometric mean	151,440
2	A105N2-4	92,575
	A112N2-6	92,575
	A90N2-9	78,120
	A97N2-7	77,420
	A103N2-9	77,105
	A105N2-2	75,705
	Geometric mean	81,935
3	A112N2-8	119,280
	A92N2-7	104,440
	A103N2-3	100,765
	A103N2-2	99,540
	A91N2-2	93,975
	A103N2-4	79,520
	Geometric mean	98,850
4	A90N2-1	136,570
	A117N2-6	126,070
	A96N2-2	122,220
	A95N2-9	115,500
	A94N2-7	114,135
	A109N2-8	112,700
	Geometric mean	120,900
5	A95N2-8	152,390
	A91N2-4	145,040
	A96N2-10	143,955
	A99N2-7	142,415
	A91N2-7	134,400
	A97N2-10	132,580
	Geometric mean	141,700
6	A88N2-7	502,985
	A111N2-6	474,985
	A99N2-3	422,590
	A111N2-8	413,980
	A111N2-9	366,870
	A89N2-7	354,165
	Geometric mean	419,200
7	A112N2-5	99,995
	A89N2-6	96,460
	A102N2-3	91,315
	A97N2-5	91,315
	A96N2-4	91,315
	A102N2-1	84,560
	Geometric mean	92,368
8	A100N2-10	72,660
	A88N2-6	71,785
	A113N2-8	71,575
	A111N2-2	65,030
	A97N2-2	62,475
	A89N2-10	56,455
	Geometric mean	66,390
9	A122N2-1	165,550
	A107N2-2	165,550
	A134N2-2	163,485
	A122N2-3	137,220
	A134N2-4	124,635
	A107N2-3	117,495
	Geometric mean	147,500
10	A122N2-7	137,060
	A123N2-9	133,420
	A134N2-6	123,620
	A132N2-7	117,145
	A134N2-9	112,000
	A133N2-6	103,040
	Geometric mean	120,600

TABLE IV.- RESULTS OF VARIABLE-AMPLITUDE FATIGUE TESTS OF 2024-T3 ALUMINUM-ALLOY SPECIMENS - Continued

(d) Peak history C

Program	Specimen	Cycles	Program	Specimen	Cycles
1	A91N2-3	100,695	2	A97N2-1	97,615
	A101N2-1	95,060		A92N2-5	87,850
	A91N2-8	93,065		A103N2-1	83,790
	A105N2-5	92,750		A92N2-8	83,265
	A96N2-9	90,825		A11N2-1	76,860
	A102N2-4	75,075		A104N2-1	67,445
	Geometric mean	90,878		Geometric mean	82,274
3	A114N2-1	94,185	4	A92N2-10	125,965
	A108N2-6	82,215		A109N2-7	118,930
	A102N2-10	81,305		A90N2-3	114,660
	A96N2-5	76,405		A100N2-1	113,540
	A95N2-7	65,905		A117N2-8	112,000
	A115N2-1	65,555		A93N2-10	101,605
	Geometric mean	76,950		Geometric mean	114,200
5	A101N2-2	125,930	6	A113N2-7	144,900
	A117N2-9	115,080		A104N2-5	139,055
	A109N2-7	113,890		A95N2-1	136,815
	A97N2-6	103,110		A99N2-4	132,790
	A105N2-1	101,780		A88N2-9	126,385
	A90N2-2	96,425		A89N2-7	114,310
	Geometric mean	108,900		Geometric mean	129,400
7	A102N2-2	108,710	8	A111N2-7	100,450
	A111N2-5	108,640		A101N2-9	90,230
	A14N2-1	100,135		A100N2-9	79,450
	A89N2-8	83,685		A97N2-3	79,450
	A95N2-6	83,685		A88N2-10	76,615
	A96N2-3	78,120		A88N2-8	74,200
	Geometric mean	93,000		Geometric mean	82,870
9	A132N2-6	172,060	10	A123N2-6	139,475
	A133N2-2	162,540		A122N2-8	124,915
	A98N2-5	159,040		A132N2-10	115,780
	A123N2-10	144,900		A122N2-6	107,730
	A92N2-1	139,265		A123N2-7	106,575
	A93N2-1	124,880		A122N2-10	100,625
	Geometric mean	149,600		Geometric mean	115,200

TABLE IV.- RESULTS OF VARIABLE-AMPLITUDE FATIGUE TESTS OF 2024-T3 ALUMINUM-ALLOY SPECIMENS - Concluded

(e) Peak history D

Program	Specimen	Cycles
1	A129N2-5	160,370
	A9N3-1	160,370
	A125N2-6	157,460
	A127N2-9	150,290
	A7N3-10	139,475
	A131N2-4	113,050
	Geometric mean	145,800
2	A108N2-5	121,590
	A128N2-2	121,170
	A127N2-4	109,550
	A129N2-10	103,495
	A102N2-6	100,520
	A128N2-7	84,490
	Geometric mean	106,000
3	A126N2-7	132,685
	A129N2-7	130,305
	A3N3-7	125,895
	A130N2-4	124,180
	A3N3-8	123,130
	A131N2-2	105,210
	Geometric mean	123,100

TABLE V.- SUMMARY OF VARIABLE-AMPLITUDE FATIGUE-TEST DATA ANALYSIS

Program number	Peak history A (DLL = 4.0)				Peak history A (DLL = 5.0)				Peak history B				Peak history C				Peak history D			
	Geometric mean life, cycles	Factor (a)	Units of time history (b)	Normalized life	Geometric mean life, cycles	Factor (a)	Units of time history (b)	Normalized life	Geometric mean life, cycles	Factor (a)	Units of time history (b)	Normalized life	Geometric mean life, cycles	Factor (a)	Units of time history (b)	Normalized life	Geometric mean life, cycles	Factor (a)	Units of time history (b)	Normalized life
1	32,140	825.6	38.9	1.00	92,580	825.6	112.1	1.00	151,440	570.9	265.3	1.00	90,878	684.0	132.9	1.00	145,800	1647.5	88.5	1.00
2	25,760	612.7	42.0	1.08	75.470	612.7	123.2	1.10	81,935	305.4	268.3	1.01	82,274	603.5	136.3	1.03	106,000	1126.3	94.1	1.06
3	25,410	699.5	36.3	.93	79,430	699.5	113.6	1.01	98,850	389.2	254.0	.96	76,950	603.0	127.6	.96	123,100	1403.1	87.7	.99
4	28,800	612.7	47.0	1.21	86,460	612.7	141.1	1.26	120,900	305.4	395.9	1.49	114,200	603.5	189.2	1.42	-------	------	----	----
5	30,400	721.1	42.2	1.08	78,610	721.1	109.0	.97	141,700	442.2	320.4	1.21	108,900	644.5	169.0	1.27	-------	------	----	----
6	102,500	825.6	124.2	3.19	211,300	825.6	255.9	2.28	419,200	570.9	734.3	2.77	129,400	684.0	189.2	1.42	-------	------	----	----
7	26,000	613.0	42.4	1.09	73,430	613.0	119.8	1.07	92,368	311.3	296.7	1.12	93,000	603.0	154.2	1.16	-------	------	----	----
8	21,350	522.0	40.9	1.05	69,100	522.0	132.4	1.18	66,390	234.3	283.4	1.07	82,870	556.7	148.9	1.12	-------	------	----	----
9	-------	-----	----	----	58,020	825.6	70.3	.63	147,500	570.9	258.4	.97	149,600	684.0	218.7	1.65	-------	------	----	----
10	-------	-----	----	----	49,430	699.5	70.7	.63	120,600	389.2	309.9	1.16	115,200	603.0	191.0	1.44	-------	------	----	----

[a]Factor = average number of positive peaks occurring after counting per unit of 5000 filtered numbers.

[b]Units of time history = $\frac{\text{Geometric mean life}}{\text{Factor}}$.

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